Multiple constraints on the age of a Pleistocene lava dam across the Little Colorado River at Grand Falls, Arizona

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ABSTRACT

The Grand Falls basalt lava flow in northern Arizona was emplaced in late Pleistocene time. It flowed 10 km from its vent area to the Little Colorado River, where it cascaded into and filled a 65-m-deep canyon to form the Grand Falls lava dam. Lava continued ~25 km downstream and ~1 km onto the far rim beyond where the canyon was filled. Subsequent fluvial sedimentation filled the reservoir behind the dam, and eventually the river established a channel along the margin of the lava flow to the site where water falls back into the pre-eruption canyon.

The ca. 150 ka age of the Grand Falls flow provided by whole-rock K-Ar analysis in the 1970s is inconsistent with the preservation of centimeter-scale flow-top features on the surface of the flow and the near absence of physical and chemical weathering on the flow downstream of the falls. The buried Little Colorado River channel and the present-day channel are at nearly the same elevation, indicating that very little, if any, regional downcutting has occurred since emplacement of the flow.

Newly applied dating techniques better define the age of the lava dam. Infrared-stimulated luminescence dating of silty mudstone baked by the lava yielded an age of 19.6 ± 1.2 ka. Samples from three noneroded or slightly eroded outcrops at the top of the lava flow yielded ^{3}He cosmogenic ages of 16 ± 1 ka, 17 ± 1 ka, and 20 ± 1 ka. A mean age of 8 ± 19 ka was obtained from averaging four samples using the $^{40}Ar/^{39}Ar$ step-heating method. Finally, paleomagnetic directions in lava samples from two sites at Grand Falls and one at the vent area are nearly identical and match the curve of magnetic secular variation at ca. 15 ka, 19 ka, 23 ka, and 28 ka. We conclude that the Grand Falls flow was emplaced at ca. 20 ka.

Keywords: Grand Falls lava dam, Quaternary, $^{40}Ar/^{39}Ar$, ^{3}He, magnetic secular variation, infrared luminescence.

INTRODUCTION

Dating Quaternary mafic volcanic materials has proven to be challenging in many cases. K-Ar and $^{40}Ar/^{39}Ar$ are the most common dating methods, but results may be difficult to interpret because so little potassium is present in these rocks and because the rocks may also contain excess Ar from mantle or crustal sources (Dalrymple and Hirooka, 1965). In some cases, the resulting age uncertainties hinder understanding of patterns of volcanism; in others they mislead interpretations of the rates of landscape change, which rely on volcanic markers for age control.

Basalt lava flows have dammed the Colorado River in the Grand Canyon at least a dozen times during the Quaternary (Dutton, 1882; McKee and Schenk, 1942; Hamblin, 1994; Dalrymple and Hamblin, 1998; Pederson et al., 2002), creating short-lived lakes (Kaufman et

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GSA Bulletin; March/April 2006; v. 118; no. 3/4; p. 421–429; doi: 10.1130/B25814.1; 8 figures; 4 tables.

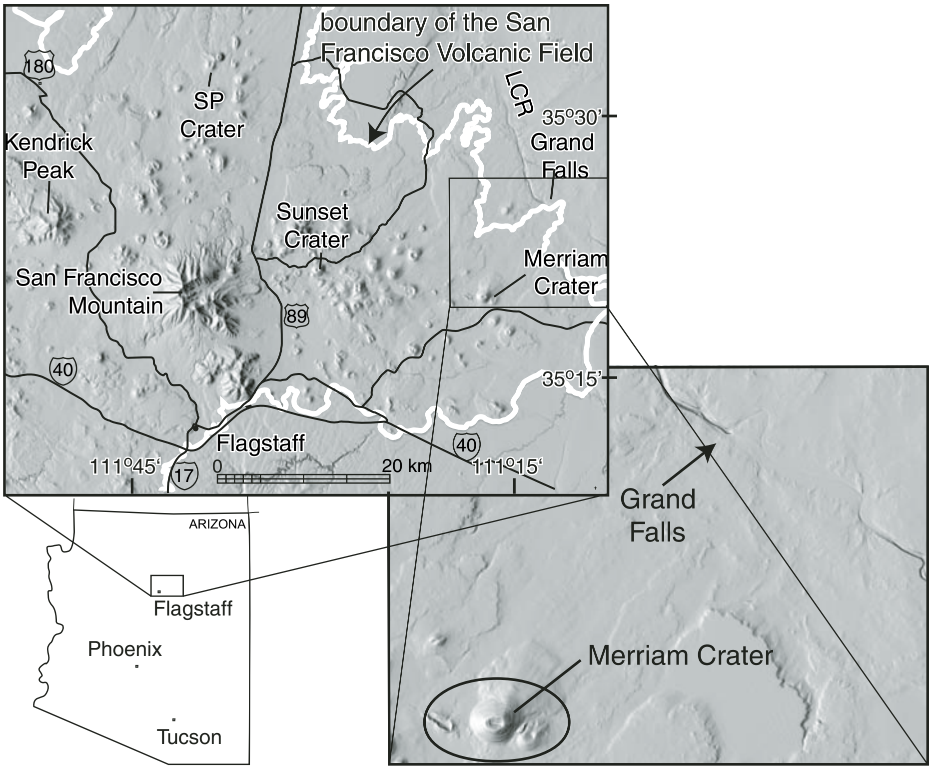

Figure 1. Digital elevation model of the eastern half of the San Francisco volcanic field (rough terrain) and adjacent areas, northern Arizona. Nearly horizontal Paleozoic and Mesozoic sedimentary rocks underlie relatively smooth landscapes east of the boundary of the volcanic field. Inset shows area of vents in the Grand Falls area: compare with Figure 2, which shows geology near the cones and extent of lava flow. LCR—Little Colorado River.

al., 2002; Fenton et al., 2002). The Little Colorado River, a tributary to the Colorado River in northern Arizona, also is the site of numerous lava dams emplaced during Pliocene and Pleistocene times. These dams provide important time markers that can be used to trace former landscapes and to gauge rates of landscape evolution, including fluvial incision.

Lava of the dam at Grand Falls (Fig. 1) yielded a whole-rock K-Ar age of 150 ± 30 ka (Moore and Wolfe, 1987; see also McKee et al., 1998). The Grand Falls dam formed when basaltic lava, herein called the Grand Falls flow, spilled into the canyon of the Little Colorado River (Colton, 1930, 1936; Moore and Wolfe, 1976, 1987; Figs. 2A and 3A). Lava filled the canyon at the dam and spilled over onto the far (eastern) rim to feed a several-meter-thick, tongue-shaped lobe that advanced ~1 km beyond. Lava also flowed ~15 km up-canyon (Plescia et al., 2001) and ~25 km down the canyon. Cross-sectional exposures across part of the lava dam reveal that the canyon was at least 65 m deep and near the level of the modern channel at that time (Fig. 2B).

Recent mapping and geomorphic assessments of the region indicate that the 150 ka age for the Grand Falls flow is inconsistent with the degree of weathering of the flow surface as well as the geomorphic position of the lava flow with respect to current base level. Accordingly, we redated the lava flow using the K-Ar method (Table 1) and then reevaluated both the new K-Ar date (293 ka ± 10 ka) and the K-Ar age reported by Moore and Wolfe (1987)[1] by applying a suite of dating techniques. These include (1) the infrared-stimulated luminescence age of clastic sediment baked by lava near the dam, (2) the cosmogenic ^{3}He age of the lava surface at the dam, and (3) the step-heating $^{40}Ar/^{39}Ar$ age of lava from the holocrystalline core of the dam. We have also matched the paleomagnetic direction of the lava with the late Pleistocene secular variation curve for the study area. The results are all consistent with a dam that formed at ca. 20 ka and strongly suggest that the earlier K-Ar age is incorrect.

GEOLOGIC SETTING

The lava of the dam at Grand Falls is part of the Pliocene to late Holocene San Francisco volcanic field (Wolfe, 1990) of northern Arizona (Fig. 1). This volcanic field is located on the Colorado Plateau, near its southern margin, and overlies a kilometer-thick subhorizontal sequence of Paleozoic and minor Mesozoic sedimentary rocks that cap Precambrian basement (Ulrich et al., 1984). The volume of volcanic rocks is ~500 km^3 (Wolfe, 1990), distributed over an area of ~5000 km^2. Rock types range from basalt to rhyolite, but basalt is dominant.

The outline of the volcanic field defines the shape of an east- to northeast-trending belt, ~100 km long and 40 km at its widest. Most of the oldest rocks (6 Ma to 5 Ma) were erupted from vents within the western third of this belt; a centroid of volcanism has subsequently migrated east-northeastward at an average rate of ~2 cm/yr (Tanaka et al., 1986). The most recent eruption created Sunset Crater basalt cinder cone and associated lava flows and fallout cinder blanket ca. A.D. 1075 ± 25 (Ort et al., 2002), within the eastern third of the volcanic field (Fig. 1). Lava that created the dam at Grand Falls vented within the most easterly part of the field, ~10 km southwest of the Little Colorado River (Figs. 1 and 2A).

Lava forming the dam was erupted from one or more of four closely spaced vents (Fig. 2A). Unambiguous identification of which of these vents is the source of lava for the dam remains elusive. The geologic maps of Moore and Wolfe (1976, 1987) suggest that flows from either Sproul Crater or adjacent Merriam Crater created the dam. Two additional (unnamed) vents at the east base of Merriam Crater, however, also appear to be possible candidates for source of the lava.

The pristine (except for scars of recent cinder mining) morphology of the constructs at all four vents and their distribution along two en-echelon northwest trends suggest that the volcanoes of this cluster were active at about the same time. All four may have erupted during a single brief episode to feed the Grand Falls lava flow. The Merriam Crater cinder cone towers 300 m above the tallest of the other three vent constructs. Because these three are not covered

[1]Because Moore and Wolfe's (1987) date of ca. 150 ka is the generally accepted age of the Grand Falls flow, through the remainder of this paper we refer only to this date, and not to the K-Ar date that we obtained.

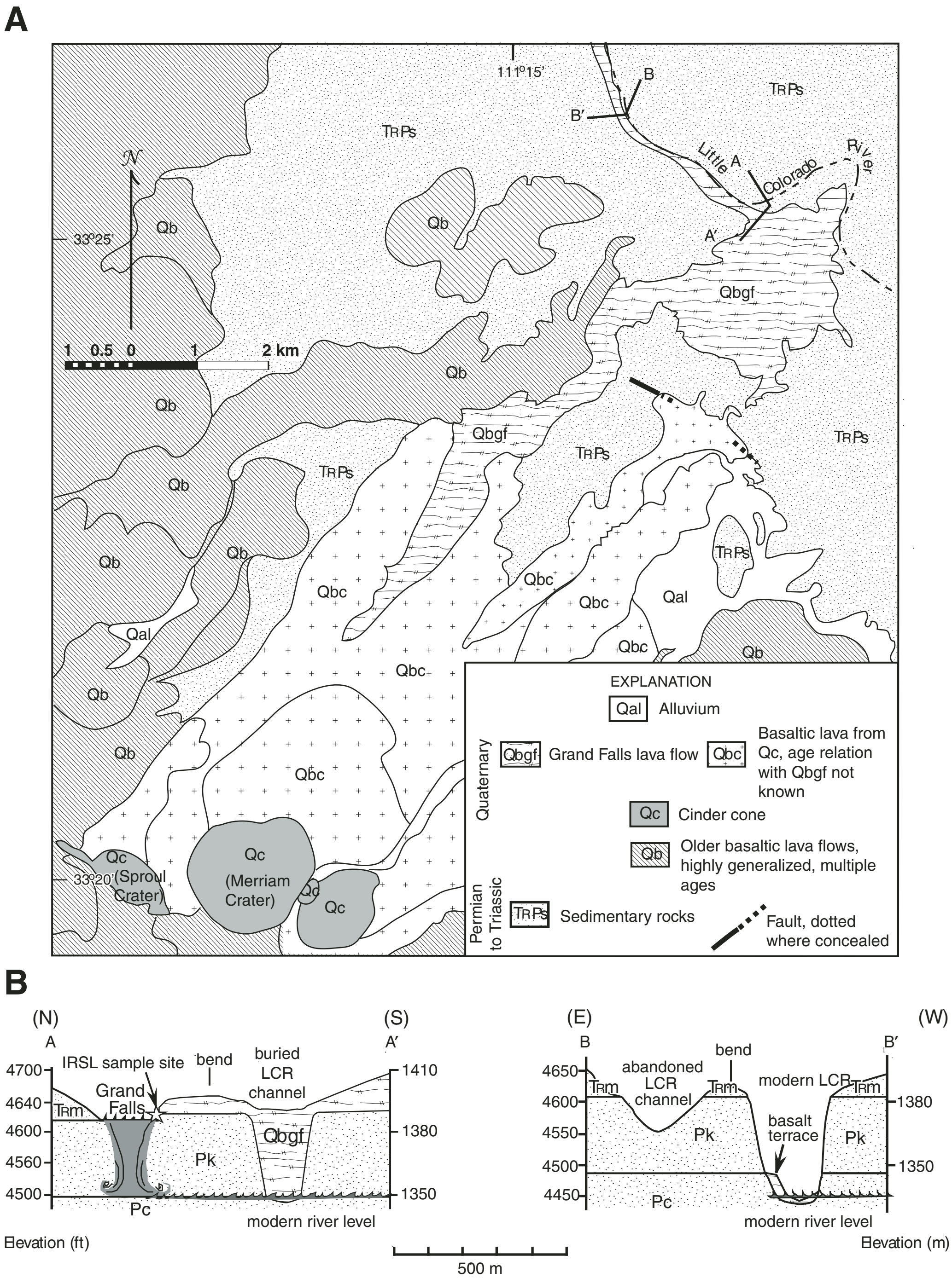

Figure 2. (A) Geologic map of the Grand Falls area, generalized from Moore and Wolfe (1976). Note finger of lava extending downstream from Grand Falls. Cinder cones (Qc) are potential source vents for Grand Falls flow. (B) Cross sections. At the dam, basalt lava completely filled the canyon of the Little Colorado River (LCR; see also Fig. 3B) and spilled over the east side onto an outcrop of silty mudstone of the Triassic Moenkopi Formation, where we collected a sample for infrared-stimulated luminescence (IRSL) dating (see section A–A′). Intracanyon basalt extends downstream and is incised to form a terrace along the canyon wall (see section B–B′; Fig. 3A). Pc—Coconino Sandstone; Pk—Kaibab Formation; TRm—Moenkopi Formation.

with Merriam Crater cinders, Merriam Crater probably is the oldest of the cluster.

The basin behind the lava dam is now filled with alluvial and possibly lacustrine sediment derived from the Little Colorado River basin (Figs. 3B and 4). The sediment buries the upstream intracanyon lava flow, and forms a very low gradient (0.08%) plain that extends ~7 km upstream from the dam, where walls of the pre-dam canyon first reappear. From this point, the present course of the river across the alluvial surface follows a path almost directly above the pre-dam gorge, and then diverts around the margin of the spillover lava lobe before cascading into the original, pre-dam channel (Fig. 3A). This cascade, Grand Falls, carries water infrequently in the present-day semiarid climate.

The amount of water potentially present in the river when the dam was formed can be estimated by a lack of deposits suggesting interaction between water and lava. Pillow lavas and hyaloclastite deposits (breccia formed by thermal quenching of magma) are lacking. The irregular fanning arrangement of axes of basalt columns that make up the bulk of the dam suggests that permeating steam produced

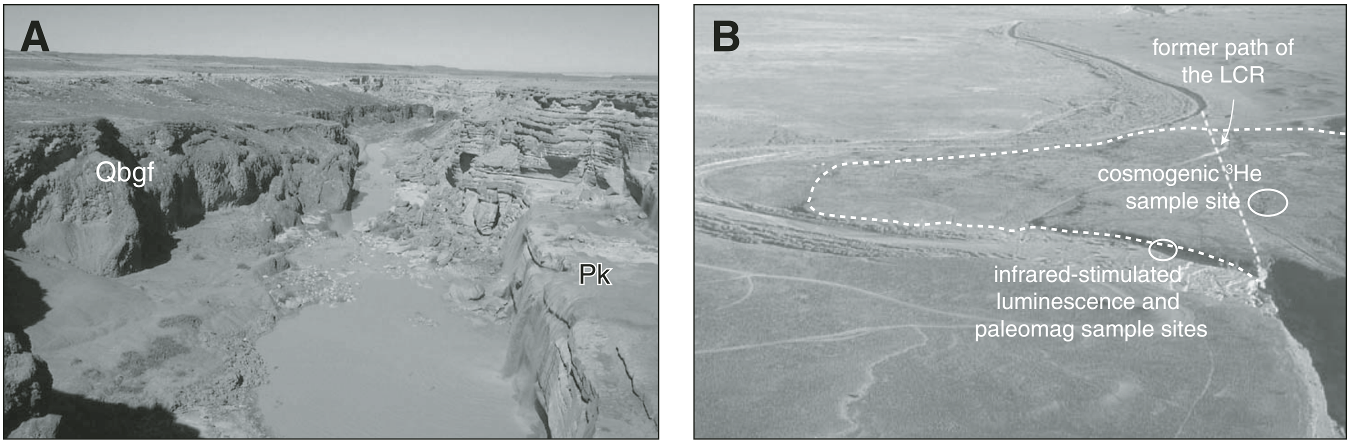

Figure 3. (A) Photo looking northwest downstream at Grand Falls and along the Little Colorado River (LCR). Note that the river has carved a channel at the contact between the Grand Falls flow (Qbgf) and the Paleozoic and Triassic rocks (Pk). (B) Oblique aerial photo, looking upstream (southeast) from Grand Falls (in the shadow at lower right). Dashed line marks the approximate path of the pre-eruption canyon beneath the lava dam. Note that the present river arcs around the edge of lava (dotted line) that spilled over onto the east rim of the canyon, before cascading into the downstream continuation of the pre-dam canyon. (Image is used with permission of Michael Collier.)

irregular shapes of isotherms during cooling and solidification of the dam when the columns were forming. Perhaps the river was a trickle or simply contained a few stagnant ponds of water during dam formation

Post-dam erosion by the Little Colorado River has carved a broad channel ~7 m deep along the outer edge of the overflow lobe of the dam. The escarpment at Grand Falls has eroded back due to headward cutting, which has produced an excellent cross-sectional exposure of the dam where it fills the former gorge. The basal contact of lava in the pre-dam gorge is not exposed at the falls. Remnants of intracanyon lava are attached to canyon walls for 1–2 km downstream from the dam. Further downstream, the 25-km-long intracanyon flow (Moore and Wolfe, 1976, 1987) forms the bed of the river and is not significantly eroded. The modern channel of the Little Colorado River has notched ~2 m below its pre-dam thalweg in at least one place, ~10 km downstream of the falls. This incision probably is a result of local retreat of a knickpoint, or the river slipping off the flow surface, rather than signifying regional-scale downcutting (Fig. 4).

IMPLICATIONS OF THE AGE OF THE GRAND FALLS FLOW

Erosional remnants of two older basaltic lava dams across the Little Colorado River are present at ~30 and 80 km downstream from Grand Falls. On the basis of whole-rock K-Ar ages of 2.39 ± 0.32 Ma and 0.51 ± 0.08 Ma for those dams, Damon et al. (1974) and Rice (1980) reported average rates of downcutting since 2.39 Ma of ~90–100 m/m.y. Applying this rate to the reported K-Ar age of 150 ± 30 ka for the Grand Falls dam (Moore and Wolfe, 1987) implies that the Little Colorado River should have incised ~14 m since the emplacement of the dam. The geologic relations, however, show little or no net regional downcutting in the vicinity of the lava flow. The localized downcutting at the dam probably took place soon after it was formed, as the Little Colorado River quickly regained its gradient (compare with Fenton et al., 2002). Either the average rate of downcutting in response to tectonic and base-level control has decreased substantially since 150 ka, or the K-Ar age of the lava dam at Grand Falls is much older than the actual age of the lava.

TABLE 1. SUMMARY OF K-Ar WHOLE-ROCK AGES

Sample number	Latitude (°N)	Longitude (°W)	K_2O (wt%)	^{40}Ar*† (picomoles/g)	^{40}Ar* (% of total Ar)	Age (ka)
1‡	35.43	111.2	0.922	0.204	4.44	150 ± 30
2§	35.6	111.3	0.919	0.388	10.5	293 ± 10

†Asterisk denotes radiogenic argon.
‡Analysis by P.E. Damon, University of Arizona; Moore and Wolfe (1987); McKee et al. (1998).
§Analysis by E.H. McKee, U.S. Geological Survey, Menlo Park.

STRUCTURE AND PETROGRAPHY OF THE GRAND FALLS FLOW

The dam, where exposed in cross section along the southwest wall of the river canyon directly opposite the lip of Grand Falls, consists of at least five emplacement (cooling) units. The bulk of the dam, in terms of vertical exposed thickness (and presumably also in terms of relative volume), is a single cooling unit of dense columnar-jointed basalt (Fig. 5). Columns are ~50 cm across and form plumose patterns defined by the gently curving axes of "bundles" of columns.

The columnar basalt is nonvesicular. It contains ~5% by volume of 0.5–1.0 mm phenocrysts of fresh subhedral and euhedral olivine in a groundmass of granular olivine, granular opaque minerals, and subparallel plagioclase laths. No glass is apparent in thin sections.

The thick plug of columnar basalt is overlain by a stack of four gently dipping basalt flows (Fig. 5), each ~1–2 m thick. Each flow has a well-defined rubbly and vesicular bottom and top. These emplacement units lack evidence of physical erosion or chemical weathering, both within the stack of flows and at the basal contact of flows with underlying columnar basalt. The flows may simply represent overlapping lobes of a single lava flow. Lateral continuity away from the cross-sectional exposure in the wall of the canyon is impossible to determine. In thin section, the flows appear identical to samples from the columnar core of the lava dam, with the exception of the presence of a few to several percent vesicles and rare plagioclase crystals several millimeters long. These crystals are rounded and encased within a reaction rim, which suggests that they are xenocrysts rather than phenocrysts.

The surface of the lava at and near the dam displays a few meters of primary constructional relief; many relatively low-lying areas of the lava surface are covered by cinder lapilli and finer sediment of eolian origin. Scattered mounds that form local highs rise 1–2 m above the general lava surface. These appear to include masses of agglutinate rafted from a vent and lava balls that have rocky cores (agglutinate?) that became coated with concentric layers of lava that accreted during flow from the vent area. Exposed surfaces on other parts of the lava include both pahoehoe and a‘a. All features not covered by eolian sediment appear to represent original or nearly original surfaces of lava that have been little weathered or eroded, if at all, since their formation.

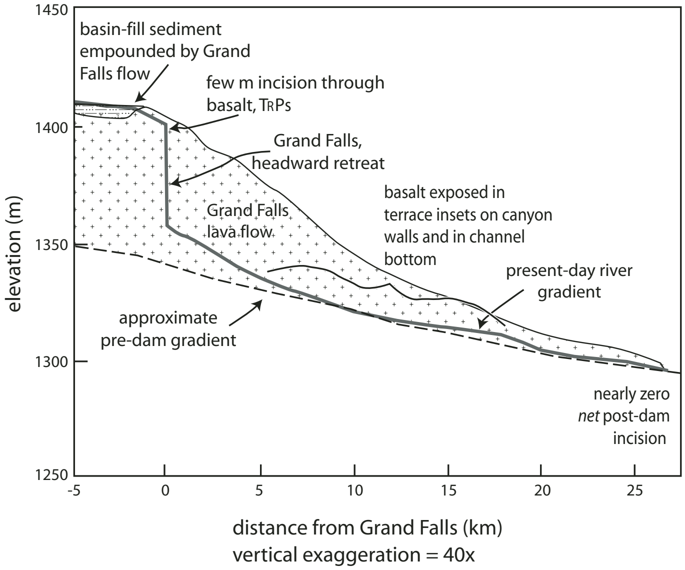

Figure 4. Sketch longitudinal cross section showing interactions of inferred paleo–stream bed, modern stream bed, and Grand Falls flow. Although the pre-flow gradient can only be broadly inferred, we believe that it lies not far below the present-day stream.

GEOCHRONOLOGY

Even when analytical and sample conditions are optimal, the numerical age of a basaltic rock younger than ca. 0.5 Ma is commonly difficult to determine accurately using ^{40}K because of the long half life of this isotope (1.25×10^9 yr) and because basalt contains so little potassium. Basalt of the Grand Falls lava dam contains ~1 wt% K_2O (Moore and Wolfe, 1987).

Some young basalts yield K-Ar or ^{40}Ar/^{39}Ar ages older than the time of their eruption because they contain mantle source region ^{40}Ar (so-called excess Ar) trapped in glassy groundmass and/or in fluid inclusions of crystals (Dalrymple and Hirooka, 1965; Damon et al., 1967; Laughlin et al., 1994; Dalrymple and Hamblin, 1998; Fenton et al., 2002). Continuing advances in the efficiency of gas-extraction lines and mass spectrometry in some cases have improved the precision and accuracy of dating young basalt based on the decay of ^{40}K (McIntosh et al., 2002). Nonetheless, caution is generally required in interpretation of K-Ar or ^{40}Ar/^{39}Ar ages, particularly those younger than ca. 0.5 Ma. Application of multiple dating techniques that have results that converge on a common age is an obvious and powerful means of helping to evaluate the accuracy of a stand-alone K-Ar age (e.g., Fenton et al., 2001).

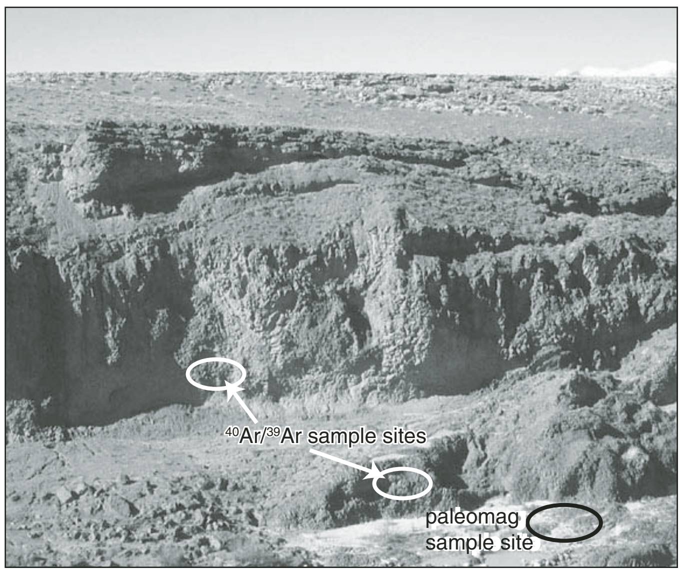

Figure 5. Exposed interior of the lava dam, looking west-southwest from the lip of Grand Falls. Horizon is defined by an eroded edge of Kaibab Limestone. Slope beneath this ledge is covered with basalt cinders. The top few meters of the lava dam consist of thin lava flows that dip to the right, gently downstream. Beneath this, columnar basalt extends to, and an unknown distance beneath, the modern river level.

^{40}Ar/^{39}Ar Ages

We collected four samples from the core zone of the lava dam (Fig. 5), at outcrops within a few tens of meters from each other. Thus, all samples are from a single emplacement unit that cooled slowly enough to minimize the content of glass in the groundmass. As noted earlier, no glass is apparent in thin sections of these rocks: complete crystallization of magma tends to reduce excess Ar in a rock.

Finely crystalline groundmass was concentrated and analyzed by the ^{40}Ar/^{39}Ar incremental-heating method, using procedures

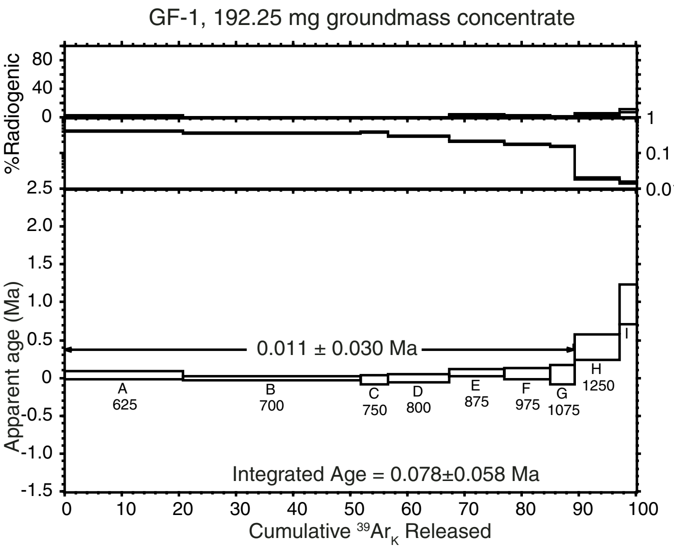

Figure 6. Example of age spectrum for sample GF-1. The weighted mean of steps A through G, which includes 90% of the released ^{39}Ar, is the preferred age. Note that the sample contains so little radiogenic Ar that the uncertainty is greater than the apparent age, highlighting the problem of dating very young basalt flows.

described by McIntosh et al. (2003) and Esser and McIntosh (2005). One sample was analyzed twice and the other three once each. All samples yielded reasonably well-defined plateau ages (Fig. 6) that range from near zero to 0.054 Ma (Table 2). During heating, the samples released so little radiogenic Ar that the analytical uncertainty, in each case, is greater than the calculated age, a result not uncommon in ^{40}Ar/^{39}Ar dating of young volcanic rocks that contain very little potassium. Nonetheless, all five ages are indistinguishable within their 2σ uncertainties. The weighted mean of these ages is 0.008 ± 0.019 Ma (Table 2; complete analytical data available in Esser and McIntosh, 2005). Although these results are less precise than desired, they indicate that the flow is much younger than the original 150 ka K-Ar date.

TABLE 2. SUMMARY OF ^{40}Ar/^{39}Ar STEP-HEATING PLATEAU AGES

Lab number	Sample number	Age (Ma)
52614	GF-1	0.011 ± 0.030
50641-01	GF-2	0.010 ± 0.060
52616	GF-3	–0.002 ± 0.030
52618	GF-4	0.054 ± 0.075
52620	GF-5	0.016 ± 0.117
Weighted mean of all five ages:		0.008 ± 0.019

Note: Samples collected at 35.7°N, 111.2°W, elevation 1344 m. Details of sample preparation techniques and analytical results are contained in Esser and McIntosh (2005).

Luminescence Age

A single sample for infrared stimulated luminescence dating (IRSL) was collected from quartz-and-feldspar–bearing silty mudstone of the Triassic Moenkopi Formation, which locally underlies the tongue of basalt that flowed over the eastern rim of the river canyon (Fig. 3B). We excavated the contact of Moenkopi Formation with the overlying basalt. A brick-red color extending several centimeters down into the Moenkopi Formation strongly suggests that the sedimentary rock was heated by the lava to at least the 300 °C required to reset the luminescence signal (e.g., Forman et al., 1994).

Luminescence geochronology is based on the time-dependent dosimetric properties of silicate minerals, predominantly feldspar and quartz (Aitken, 1985, 1998). When luminescence-free silicate minerals are shielded from exposure to light or heat in excess of 300 °C, ionizing radiation from the decay of naturally occurring radioisotopes of U, Th, and K produces free electrons, which become trapped in crystallographic charge defects in the silicate crystals. Light (or heat) excitation of such shielded crystals results in recombination of this stored charge, and the process of recombination emits measurable luminescence. The intensity of this emission is calibrated in the laboratory to yield an equivalent dose (D_e), which is divided by an estimate of the radioactivity that the affected crystals received during burial (dose rate, D_r) to yield a luminescence age. D_r was estimated by analyzing the concentrations of ^{40}K, U, and Th within the surrounding Moenkopi Formation (Table 3).

We calculated errors for D_e determinations by using a nonlinear least-squares routine, based upon the Levenberg-Marquardt method (Marquardt, 1963), in which inverse variance weighted data are modeled by a saturating-exponential function (Huntley et al., 1988). Errors were generated for each D_e calculation in a variance-covariance matrix. The resultant uncertainties in D_e reflect dispersion in the data and random errors from modeling the data by a saturating-exponential function. We used standard statistical weighing procedures to calculate an average D_e and associated error. Our final calculated age is 19.6 ± 1.2 ka (Fig. 7, Table 3).

Cosmogenic ^{3}He Ages

We collected three samples from the flattest, highest parts of three different agglutinate structures described previously. The sampled sites stand ~1.5–1.7 m above the surrounding lava-flow surface and probably were never buried by eolian deposits. Variable thicknesses of lava were collected, but only the top 4 cm were used in ^{3}He analysis.

Olivine separates were prepared in accord with methods described in Cerling et al. (1999). The released gas was purified using getters and cryogenic traps. ^{3}He/^{4}He measurements were made on the University of Utah's MAP-215 noble-gas mass spectrometer, fitted with an electron multiplier and pulse-counting electronics (Table 4). Crushed phenocrysts were melted at 1400 °C in a double-walled modified Turner furnace. ^{3}He/^{4}He ratios were standardized against the SIO-MM standard at 16.45 R_A (where $R_A = 1.386 \times 10^{-6}$, the air ratio). All values were adjusted for interference peaks, and instrumental and extraction blanks (Poreda and Cerling, 1992).

The amount of cosmogenic ^{3}He in the sample, referred to hereafter as ^3He_c, was then calculated from:

$$^3He_c = {}^4He\left[\frac{^3He}{^4He_m} - \frac{^3He}{^4He_i}\right],$$

where the subscripts c, m, and i represent the cosmogenic, melted fraction, and inherited values, respectively (Cerling et al., 1994). Inherited values do not include radiogenic He. The contribution of radiogenic ^{3}He/^{4}He is significant in old rocks with young (younger than 10–20 ka) exposure ages but is not significant for young (younger than 500 ka) basalts (Cerling et al., 1999; Fenton et al., 2002). We used

TABLE 3. DOSE-RATE AND EQUIVALENT-DOSE (D_e) DATA USED FOR IRSL GEOCHRONOLOGY OF SILTY MUDSTONE HEATED BY BASALT LAVA (SAMPLE #UIC-716)

Th† (ppm)	U† (ppm)	Unsealed: sealed‡	K_2O§ (%)	a value#	Dose rate†† (Gy ka^{-1})	D_e (Gy)	Age (ka)
7.35 ± 0.87	3.43 ± 0.21	1.03	4.08 ± 0.03	0.05 ± 0.01	5.74 ± 0.30	112.4 ± 1.1	19.6 ± 1.2

Note: IRSL— infrared stimulated luminescence. Sample collected at 111.19°N, 35.7°W, elevation 1383 m.

The dose rate for our sample was estimated by analyzing the concentration of ^{40}K, U, and Th in the sample. The U and Th contents were determined by thick-source alpha counting, which assumes secular equilibrium in the decay series. The radioactive potassium component (^{40}K) was determined from the assayed K_2O content of the sediment by inductively coupled plasma–mass spectrometry by Activation Laboratory, Ontario, Canada. A cosmic ray component (0.16 ± 0.02 Gy/ka) was included in the estimated dose rate following the techniques of Prescott and Hutton (1994). The alpha efficiency (a value; Aitken and Bowman, 1975) was determined under infrared stimulation for the polymineral fraction and is 0.05 ± 0.01.

The D_e was determined on the polymineral, fine-grained (4–11 μm) fraction by the total-bleach method, as described by Forman and Pierson (2002). The residual level is the thermal reset level, which is also the background count for IRSL measurements. Samples were preheated at 160 °C for 10 h. Measurement of the IRSL signal was delayed at least one day after preheating. Tests for stability of the laboratory-induced and preheated IRSL signal, after more than 32 d storage, revealed insignificant (<5%) reduction in signal, indicating stability of the laboratory and natural infrared emissions. Optical stimulation was accomplished using infrared emissions (880 ± 80 nm) from a ring of 30 diodes with an estimated energy delivery of 17 mW cm^{-2}. The output from the diode array at the sample position was calibrated by measuring the current induced in a silicon photodiode (Telefunken BPW-34) connected to a resistive circuit. We measured the resultant blue emissions (with three, 1-mm-thick Schott BG-39 and three, 1-mm-thick Corning 7 59 glass filters, which transmit less than 10% transmission below 390 nm and less than 10% above 490 nm) from the sediments. The background count rate for measuring blue emissions was low (80 counts s^{-1}), with a signal-to-noise ratio of greater than 20. Samples were excited for 90 s, and the resulting IRSL signal was recorded in 1 s increments.

†U and Th values calculated from a count rate of 0.692 ± 0.033 ks/cm^2 ks, assuming secular equilibrium.

‡Ratio of bulk account rate under unsealed and sealed counting conditions; >0.95 indicates little or no Ra loss.

§K_2O% determined by flame photometry, Activation Laboratory, Ontario, Canada.

#Measured alpha efficiency factor as defined by Aitken and Bowman (1975).

††Assumes a moisture content of 10 ± 3%.

a production rate of 115 ± 4 atoms/g/yr for ^3He_c in olivine adjusted for both high latitude and sea level for the past 17.8 ka (Cerling and Craig, 1994). Because the production rate increases as elevation and latitude increase, we scaled our production rate (Lal, 1991) for the elevation and latitude of Grand Falls. Studies have shown that the ^3He_c production rate has not varied by more than 10% during the past 150 k.y. (Ackert et al., 2003; Dunai and Wijbrans, 2000).

Under these conditions, ^3He_c ages of our samples are 16 ± 1 ka, 17 ± 1 ka, and 20 ± 1 ka (reported to 1σ). The sample that yielded the youngest age came from an agglutinate structure that shows evidence of possible exfoliation. Thus, we may have collected the sample from a surface that has experienced minor erosion.

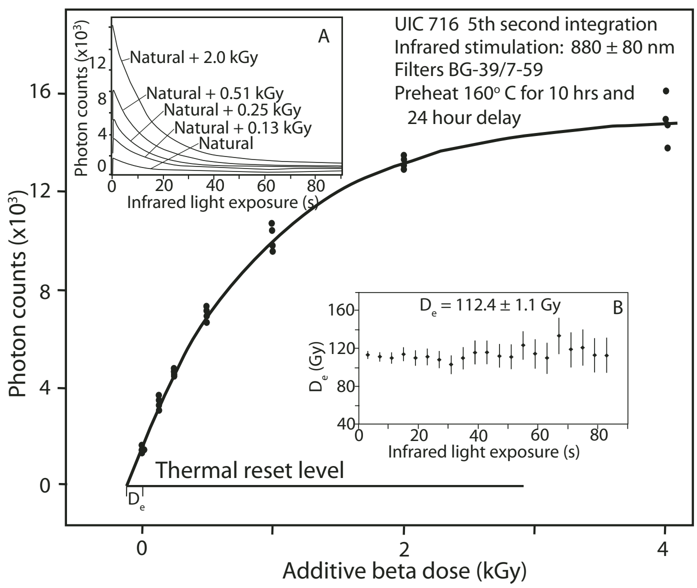

Figure 7. Derivation of equivalent dose (D_e) by the additive-dose method, for sample of silty mudstone of the Triassic Moenkopi Formation at Grand Falls. Photon-count luminescence values are for 5 s of stimulation by infrared light exposure. Inset A shows change in luminescence with infrared light exposure time (shine-down curves) for natural and additive-dose treatments. Inset B shows D_e values for multiple infrared light exposure times (plateau plot), including after 5 s, which is depicted in the main plot.

Paleomagnetic Correlation

A total of 40 core samples for paleomagnetic studies were drilled at a site on the thin tongue of lava that spilled onto the east rim of the pre-dam canyon (Fig. 3B), at a site near the base of the falls where the columnar-jointed core of the lava dam is exposed (Fig. 5), and at the Merriam Crater vent. Pilot samples were progressively demagnetized in alternating field (AF) until each was free of secondary components. Blanket AF cleaning fields (20–40 mT) were then performed on each of the remaining samples. Weakly held isothermal remanent magnetizations (IRM), probably due to lightning strikes, were removed by the laboratory treatment. Within analytical uncertainty, samples from these three sites yielded nearly identical paleomagnetic orientations of 34° inclination and 10° declination (Fig. 8). This orientation is unusual for the area within the time interval between 14 ka and 32 ka. We compared the orientation of the magnetic field preserved by the basalt with the continuous record of secular variations previously obtained from drill core at Mono Lake, California (Fig. 8). We then reduced Mono Lake inclinations by 2.5 degrees to adjust for more southerly latitude of Grand Falls. Our drill-core samples match the path of magnetic secular

TABLE 4. ^3He_c EXPOSURE AGES FROM OLIVINE SEPARATES AND LOCATIONS AND ELEVATIONS OF COSMOGENIC SAMPLES COLLECTED FROM THE SURFACE OF THE GRAND FALLS LAVA FLOW

Sample	Latitude (°N)	Longitude (°W)	Elevation (m)	R/R_A† crush	R/R_A† fusion	^4He ± analytical error‡ (10^9 atoms/g)	^3He_c ± analytical error‡,§ (10^6 atoms/g)	^3He_c (%)	Production rate# (atoms/g/yr)	Cosmogenic ^3He_c age ± uncertainty†† (ka)
AZ01-GF-107	35.43	111.20	1386	6.08	21.36	236.78 ± 11.84	5.21 ± 0.26	71.3	322	16 ± 1
AZ01-GF-108	35.43	111.20	1386	6.08	25.25	203.31 ± 10.17	5.61 ± 0.28	75.9	322	17 ± 1
AZ01-GF-109	35.42	111.20	1386	6.08	23.72	259.90 ± 13.00	6.60 ± 0.33	71.9	322	20 ± 1

†$R_A = 1.38 \times 10^{-6}$; it is assumed that all ^4He is mantle-derived, and an average R/R_A crush value of 6.08 was used from data from the nearby Uinkaret volcanic field (Fenton et al., 2001, 2002).
‡Analytical error ≤5%; includes corrections for precision of mass spectrometer, blanks, and standards.
§ ^3He_c atom concentration corrected to the surface of each sample, accounting for self-shielding.
#Production rate is corrected for skyline shielding resulting from surrounding topography.
††Uncertainty includes error propagation of analytical error and production rate uncertainty (5%).

variation at ages of ca. 15.5 ± 1, 19 ± 1, 23 ± 1, and 28 ± 1 ka.

DISCUSSION

The four methods employed in this study give the mutually consistent result of ca. 20 ka for the Grand Falls lava flow. This number is substantially different from the original, generally accepted 150 ± 30 ka age provided by Moore and Wolfe (1987), which was the product of a single dating method.

The question remains of how to decide what relative weight to apportion to each dating technique in trying to accurately define when the lava dam formed. Each technique includes its own set of assumptions and uncertainties. We consider various arguments and potential problems here.

1. Interpretation of the accuracy of the luminescence age is difficult, in large measure because it is a single result. Analyzing multiple samples of baked Moenkopi Formation rocks would have been preferable, in order to evaluate the reproducibility of the results. Perhaps future field exploration will uncover additional datable samples to help evaluate the reproducibility of the age. Nonetheless, the 19.6 ± 1.2 result is consistent with the 19 ± 1 ka paleomagnetic match (Fig. 8).

2. In addition to uncertainties in the history of production rates of cosmogenic ^3He through time, confidence in the idea that a surface-exposure age accurately reflects eruption age depends on knowledge of the exposure and erosional histories of the original lava surface. Our samples may have come from slightly eroded, rather than original, surfaces, therefore our results (16 ± 1, 17 ± 1, and 20 ± 1 ka) are probably best considered minimum ages. Our evaluation of the outcrop from which a sample yielded the 16 ± 1 ka age is that the original surface may have been eroded. If the sample that yielded a 20 ± 1 ka age is from a noneroded surface, as we interpret to be the case, this result is consistent with the 19 ± 1 ka paleomagnetic match, as is the 17 ± 1 ka exposure age, within the uncertainties.

3. Because the $^{40}Ar/^{39}Ar$ technique is ill suited for such young rocks of low potassium content, the $^{40}Ar/^{39}Ar$ results provide the least-precise constraint on the time of lava dam formation. Nevertheless, the five independent analyses provide the greatest statistical leverage in evaluating these results, and at the 2σ confidence level indicate that the lava dam is no older than 27 ka (Table 2). This age is consistent with all of the paleomagnetic matches.

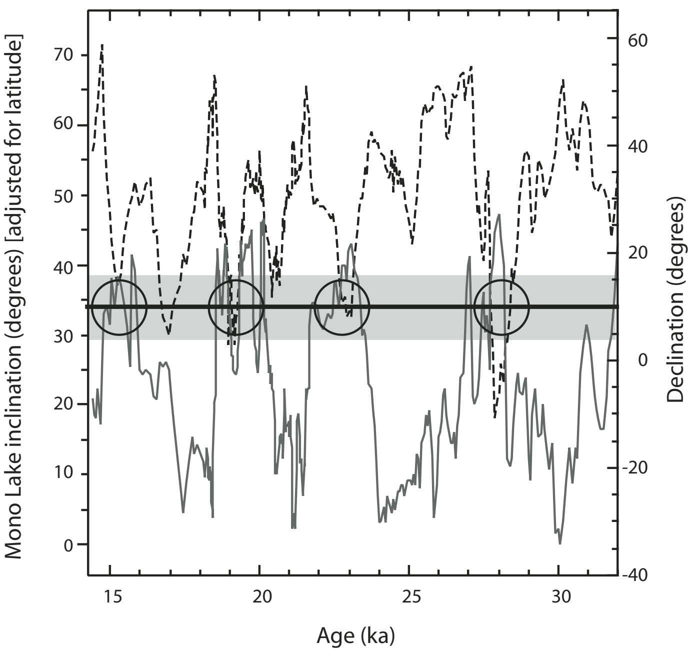

Figure 8. Record of secular magnetic variation 32–14 ka (dashed line for inclination and solid line for declination) extrapolated to the Grand Falls area. Record is derived from that preserved in well-dated cored sediments of Mono Lake, California (Lund et al., 1988). Heavy horizontal line (shading indicates uncertainty of ±5°) plots the average inclination and declination in lavas of the dam at Grand Falls and at Merriam Crater. Magnetic direction of Grand Falls area lavas coincides with that of magnetic variation (circles along horizontal line) at 15.5 ± 1 ka, 19 ± 1 ka, 23 ± 1 ka, and 28 ± 1 ka.

Because three of the four techniques we used gave a reasonable age of 19–20 ka, we conclude that the lava dam formed at ca. 20 ka. Though a unique age determination with reference to the magnetic secular variation curve alone is impossible, the paleomagnetic constraint adds an additional and important degree of confidence in this conclusion.

The much older whole-rock K-Ar age of 150 ± 30 ka reported by Moore and Wolfe (1987) is from a sample of one of the xenocryst-bearing lavas. The age may reflect excess Ar inherited from incompletely degassed magma from the mantle source region and/or contamination contained in xenocrysts. For Ar-based geochronology, the general problem of excess Ar in basaltic lavas of the San Francisco volcanic field may be widespread. For example, Conway et al. (1997) reported step-heating $^{40}Ar/^{39}Ar$ ages that are significantly younger than the whole-rock K-Ar ages reported by Damon et al. (1974) for samples from the same eruptive units. A case-by-case comparison is needed before the extent of the problem is known. However common excess Ar may be in lava of the volcanic field, caution is advised in all time-related generalizations about the growth of the field, including interpretation of the 100 m/m.y. rate of regional downcutting calculated from whole-rock K-Ar ages for samples from the two older lava dams along the Little Colorado River (Damon et al., 1974; Rice, 1980). The reinterpreted, much younger age of the Grand Falls lava flow and the lack of evidence of significant net incisions are consistent, within errors, with the average downcutting rate calculated for the areas of the lava dams downstream.

ACKNOWLEDGMENTS

We thank Kelly O'Connell Stroker for helping us understand the extent of the lava flow that dammed the river…especially the now-buried upstream intracanyon finger of lava. Reviews by Robert Webb, *GSA Bulletin* associate editor Jim O'Connor, and an anonymous reviewer helped us clarify our thinking and the manuscript and are gratefully acknowledged.

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Manuscript Received by the Society 11 February 2005
Revised Manuscript Received 2 June 2005
Manuscript Accepted 13 July 2005

Printed in the USA